[redacted]

7. TURBOPUMPS FOR HIGH-ENERGY PROPELLANTS

By Ambrose Ginsburg, Ward W. Wilcox, and David G. Evans

INTRODUCTION

As pointed out repeatedly during the preceding papers, the fixed weight of the rocket propulsion engine must be kept to an absolute minimum. One of the components whose weight might be reduced is the turbopump. The design of pumps for liquid propellants, the turbines that drive them, and the matching of the two into a turbopump unit are considered herein.

In order to provide an illustrative example with actual weights, a mission was selected that remained the same for all propellant combinations. The mission specified a 10,000-pound payload in a satellite orbit 300 miles above the Earth. For this mission the quantity of propellants is large, but in each case a single turbopump was considered with the pump delivery pressure taken as 700 pounds per square inch at 70 percent efficiency. The liquid propellants for which component weights were determined are RP-1 - oxygen, hydrogen-oxygen, and hydrogen-fluorine. For the fixed mission, propellant combinations with a low specific impulse had correspondingly greater capacity requirements.

PUMP DESIGN CONSIDERATIONS

In this analysis only single-stage centrifugal pumps will be considered. Except for hydrogen, the pressure requirement of 1000 pounds per square inch virtual head was well within the capability of a single-stage centrifugal pump. For hydrogen this pressure requirement probably represents an upper limit beyond which multistaging would be necessary. For all the pumps shown, the conservative design practice of stationary pumps has been extended greatly into areas now representing the state of the art in the rocket-turbopump field.

The two principal hydrodynamic factors that limit pump performance are cavitation and the extent to which a pump blade may be loaded before serious flow separation occurs. The occurrence of cavitation on a hydrofoil is shown schematically in figure 1. The free-stream fluid is cavitation free. As flow accelerates over the suction surface of the blade,

[redacted]

[redacted]

the local pressure decreases. If the local static pressure falls below the vapor pressure of the liquid, incipient cavitation or local boiling will occur first at the point of lowest pressure. The amount of local pressure drop below the stagnation pressure that may take place before the boiling point is reached is called the suction head and is designated by the symbol H_{sv}. That is, this much pressure may be converted into velocity relative to the blade before incipient cavitation. The velocity along the blade is increased both by increasing rotational speed or by increasing the volume flow through the pump.

4793-I

A semi-empirical parameter representing similar flow and cavitation conditions in geometrically similar pumps is termed the suction specific speed S and is written as

$$S = \frac{n\sqrt{Q}}{H_{sv}^{3/4}}$$

where

n rotational speed, rpm

Q flow capacity, gal/min

The higher the suction specific speed of a pump, the higher the maximum rotational speed and volume flow may be for a given suction head.

Conventional practice in pump design fixed the limit of pump operation at incipient cavitation, and the specified suction specific speed was defined for incipient cavitation. Suction specific speeds of the order of 10,000 are used in this conventional practice. Pumps designed on this basis are heavy. However, pump designs that can tolerate some cavitation without undue losses in efficiency have been developed and applied successfully to a variety of fluids including liquid oxygen. Suction specific speeds with tolerable cavitation up to 30,000 have been obtained, thus permitting lighter pump designs. However, the problem is whether hydrogen and fluorine pumps can operate satisfactorily at this level of cavitation as represented by a suction specific speed of 30,000.

When a pump is operating with fully developed cavitation, the point of incipient cavitation lies near the nose of the blade and is followed by a region of pressure which is equal to or less than vapor pressure. The cavitation bubbles grow in transit through this low-pressure region. Recent advances in missile pump design, for example, liquid-oxygen pumps, have resulted in satisfactory performance under these cavitation conditions. A comparison of the physical properties of liquid hydrogen with liquid oxygen shows this bubble growth to be less for hydrogen than for

[redacted]

[redacted]

oxygen. (The principal physical properties involved are the latent heat of vaporization, specific heat, absolute temperature, liquid density, and molecular weight. This matter is discussed in detail in ref. 1.) For these reasons the suction specific speed of 30,000 used successfully in oxygen pumps can be expected to be satisfactory for hydrogen pumps.

The properties of liquid fluorine are about the same as liquid oxygen. Therefore, a suction specific speed of 30,000 is used in this study for fluorine pumps. However, experience may show that the high rate of pump corrosion and erosion provided by liquid fluorine under cavitating conditions may ultimately require the use of larger and heavier noncavitating pumps.

The second hydrodynamic design limit for pumps is that of "blade loading." The term "blade loading" can best be described by considering the variation of pressure over the surfaces of an axial-flow pump blade as shown in figure 2. The pressure difference across the blade provides the force to turn and thereby to do work on the fluid. A critical condition exists on the suction, or upper, surface of the foil. If the pressure rise is too rapid, the boundary layer separates from the surface of the hydrofoil. Considerable energy is lost in the turbulent eddy motion of this separated fluid. Further losses result when the main flow and the separated boundary layer eventually mix to form a uniform flow downstream. With respect to efficient pump operation, the blade loading must be limited to prevent separation.

The use of a centrifugal pump eases the problem somewhat, since the pressure rise that results from increase in radius of rotation (that is, centrifugal force) does not contribute to separation. For a centrifugal pump, it is convenient to consider the tendency for separation on the basis of the velocity of the fluid relative to the rotating blade of the pump as shown schematically in figure 3. The flow is accelerated near the nose and then decelerates or diffuses to the trailing edge. If this deceleration is too rapid, the boundary layer will separate from the suction surface.

Simplified theoretical techniques have been developed which permit the designer to predict this velocity distribution within a given centrifugal pump. Incompleteness of boundary-layer theory and the complex three-dimensional geometry, however, prevent the designer from establishing an exact value for the limiting deceleration.

For the present pump analysis, a somewhat more empirical approach to the loading limit was taken. The approach was based primarily on past experience in the pump field. The loading was specified on the basis of two factors that influence the loading of the blades: (1) the

[redacted]

[redacted]

rotor-tip-to-inlet-diameter ratio (that is, the extent to which centrifugal force can be utilized to obtain head rise), and (2) the degree of turning done by the blade.

For pumps for heavy fluids such as fluorine, oxygen, and RP-1, a diameter ratio of 1.2 was used with the blades backward swept. The light fluids, such as hydrogen, require much greater head rise for the same pressure. In order to provide more turning, the blades are turned to the radial direction. The use of radial blades means a higher outlet-to inlet-diameter ratio must be used to avoid exceeding a loading limit. For hydrogen pumps, this diameter ratio was taken to be 2.0.

4793-I

No mention has been made of the effect of fluid properties on the loading limit. However, it is felt that the fluid properties of hydrogen will be favorable to the delay of separation. This opinion, which is based on the fact that the kinematic viscosity of hydrogen is comparable to that of oxygen, and only one-fifth that of water, leads to a certain amount of confidence that the loading characteristics of hydrogen will be at least as good as those fluids that have been used in the past.

For the pumps considered herein, customary stress and rotational-speed limits have been used. These hydrodynamic limits of cavitation and loading can now be used to determine the weight of pumps.

Examination of a variety of pump designs showed that pump weight was approximately proportional to the pump diameter to the 9/4 power:

$$\text{Pump weight} \sim D^{9/4}$$

Also there was a fairly constant relation between the pump diameter and the impeller diameter. For this analysis this ratio was considered to be 1.35. The impeller-outlet diameter is fixed by the head requirement and the rotational speed as follows:

$$\Delta H = C_u \frac{U_T^2}{2g}$$

where

ΔH virtual head, ft

U_T tip speed, π (diam.)(rpm)

C_u coefficient defined by this expression and indicative of the outlet vector diagram

[redacted]

Substituting and rearranging, for constant C_u,

$$\text{Pump weight} \sim \frac{\Delta H^{9/8}}{n^{9/4}}$$

However, the rotational speed is limited by cavitation as represented by the suction specific speed equation given previously. For a given flow quantity and value of S,

4793-I

$$n = \frac{SH_{sv}^{3/4}}{\sqrt{Q}}$$

Finally, the following equation results:

$$\text{Pump weight} \sim \frac{\Delta H^{1.125} Q^{1.125}}{S^{2.25} H_{sv}^{1.69}}$$

That is, pump weight is proportional to head and flow capacity and inversely proportional to suction specific speed and suction head.

The exponents of head and flow capacity are only slightly greater than 1; therefore, weight varies almost directly with flow and head requirements. In figure 4 the effect of the suction specific speed and the suction head on pump weight are shown for a large hydrogen pump at a constant head and flow. A very large decrease in weight accompanies a change in suction specific speed from approximately 10,000 to 30,000. This is a large gain, but that has already been obtained in oxygen pumps as pointed out earlier. Because the suction head is an exponential term, its influence becomes greater at low absolute values. From a pump standpoint, the low values of suction head should be avoided.

Thus far, the influence of cavitation limits on pump weight has been discussed but the loading limit has been ignored. The influence of loading limits may be demonstrated for a large hydrogen pump by figure 5. On a logarithmic plot of pump weight against suction head, lines of constant suction specific speed S fall on straight lines with a slope of the exponent 1.69. Such lines are shown for values of S of 10,000, 20,000, and 30,000. If a value of S of 30,000 is considered to be the cavitation limit, all the area to the left of the 30,000 line is cavitation limited. The dashed line in figure 5 represents the diameter-ratio limit of 2. Below this line the ratio of outlet to inlet diameter is less than 2 and the pump is loading limited. The intersection of these two limit lines may be shown to be dependent on the head requirement. The minimum-weight pump for a given flow and head requirement is then defined by the cavitation and loading-limit curves.

In a similar manner, limit lines may be established for the high-density fluid pumps where the diameter ratio was chosen as 1.2 with the backward-swept blades. For the low diameter ratio, the intersection point of the cavitation and loading-limit curves occurs at a high value of suction head. At very low values of suction head, where diameter ratio must be above 2, it is again profitable to minimize pump weight by changing to radial blades. Thus, the minimum-weight-pump curves for heavy fluids have two inflection points.

These curves can now be used to establish the effect of the properties of the various propellants on pump weight. A plot of pump weight per unit flow rate is given in figure 6 for hydrogen, RP-1, oxygen, and fluorine. Although the flow capacity of each of these pumps is different, corresponding to the original mission calculations, the effect of flow rate on these curves is secondary and does not alter the order of magnitude at any suction head. However, it is probably important to note that pump weight per unit flow rate does not generalize exactly and that the size of the pump does have some effect. From figure 6 it is evident that hydrogen pumps are much heavier for a given flow rate, primarily because of the loading limitation at higher suction heads. In fact, the weight per unit flow is arranged in the order of fluid density. 4793-I

The component weight parameter that describes the effect of component weight on the rocket-vehicle gross weight is the ratio of component weight to total propellant weight. In figure 7 this ratio is shown as a function of suction head for two mixture ratios of the hydrogen-fluorine combination. For 14 percent hydrogen, the hydrogen pump is heavier than the fluorine pump at high suction heads and has equivalent weight at low suction heads. When the percent of hydrogen is reduced to 6, the hydrogen pump is the lighter pump at all values of suction head. It appears, then, that the weight increase due to use of hydrogen may be minimized at the lean mixture ratios. Also, the available suction head at the pump inlet is shown to be the most important variable affecting pump weight.

TURBINE-DESIGN CONSIDERATIONS

The turbine has a unique problem as compared with the pump: The turbine driving fluid must come from propellant aboard the missile. Thus, the turbine must be developed from two considerations, the weight of propellant it uses and the weight of the turbine itself.

The significance of turbine flow is shown in figure 8 for a theoretical mission. Hydrogen and fluorine are used as the propellants. The figure shows the percent increase in missile gross weight from a gross weight with zero turbine flow as a function of the turbine flow in percent of pump flow. .For every percent increase in turbine flow,

[redacted]

the missile gross weight increases 4 percent, thus indicating a considerable effect of turbine flow on the over-all gross weight.

Thus, keeping the turbine flow as low as possible is desirable. However, turbine weight is affected by turbine flow as illustrated in figure 9. As the turbine flow is reduced, the required work per pound of flow (specific work) increases. To achieve this increase in specific work output within given efficiency and pressure-ratio limits, additional turbine stages must be utilized, as illustrated in the figure. This increase in the number of stages increases the turbine weight and results in the observed trend.

Since turbine weight and turbine flow are interdependent, consideration of their combined effect is necessary. Figure 10 is the same plot as figure 8 with the combined turbine-flow and turbine-weight effect on the gross weight shown as a solid line. The dashed line is the same as that previously shown where only turbine flow was considered. The difference between these two curves is the effect of turbine weight. A point is reached where the increase in gross weight due to turbine weight becomes greater than the reduction due to turbine flow. The curve thus shows a minimum region. This region of minimum missile weight is termed the optimum area for the turbine.

With only turbines in this optimum range considered, turbine characteristics for different propellant combinations will be examined.

First, the turbine flow rate, which has been shown to be important, varies with propellants. Figure 11 illustrates a comparison of the required turbine flow for RP-1 - oxygen, hydrogen-oxygen, and hydrogen-fluorine propellant combinations. All the values are for the same mission. The turbine-flow comparison is made on the left of the figure. Shown in the center is the turbine horsepower per pound of pump flow, which is termed specific power. On the right is the specific heat of the turbine driving fluids, considering fuel-rich mixtures at 1400° F turbine-inlet temperatures.

RP-1 - oxygen and hydrogen-oxygen have equal turbine flows, whereas hydrogen-fluorine has less. The explanation is noted from the power requirements and the specific heats of the fluid combinations. The RP-1 - oxygen requires considerably less pump power, but it also has a low value of specific heat. The hydrogen-oxygen pump-power requirement is high, but the specific heat is also high. The net effect makes the turbine-flow requirements the same for both the RP-1 - oxygen and the hydrogen-oxygen propellants. Conversely, the hydrogen-fluorine combination, as compared with the hydrogen-oxygen, requires less turbine flow because the pumping power is reduced owing to less hydrogen being pumped, whereas the specific heat is still high. The result is that the hydrogen-fluorine propellant combination has a definite turbine-flow advantage. Although it

[redacted]

may appear that these turbine flows are a small percentage of the total (0.5 to 0.8 percent) and are not significant, it must be remembered that the turbine driving fluid is fuel rich in order to keep the temperature down, and is approximately 50 percent hydrogen. If, for example, a propellant combination of 6 percent hydrogen and 94 percent fluorine is used, the turbine is using 4 percent of the hydrogen aboard. This is a significant value in terms of tankage required to contain the turbine driving fluid.

Next to be considered is the turbine size and weight trends for the different propellant combinations. Figure 12 illustrates schematically the turbine configurations in terms of required number of stages and diameter. The RP-1 - oxygen turbine is by far the largest in diameter but with considerably fewer stages. Its large diameter is related to the large missile propellant flow rate required for this low-energy propellant in order to achieve the necessary total impulse. The multistage hydrogen-oxygen and hydrogen-fluorine turbines are necessary because of increased specific-power requirement. These multistage turbines illustrate a region for research directed toward the achievement of increased work per stage while maintaining high efficiency.

A comparison of turbine weight for four propellant combinations is shown in figure 13. Turbine weight is presented as a ratio of turbine weight to total propellant weight. The hydrogen-oxygen weight ratio is three times that of the RP-1 - oxygen. The hydrogen-fluorine combination is shown for two values of hydrogen, 14 and 6 percent of total propellant weight. This reduction in hydrogen permits a 30-percent reduction in turbine weight, assuming the total propellant weight to remain unchanged. The turbine-weight ratio of the 6 percent hydrogen-fluorine and of the RP-1 - oxygen are of the same order.

MATCHING OF PUMP AND TURBINE

Heretofore, each component of the turbopump has been considered separately. In order to make a useful device, the turbine and the two pumps must be combined in such a way that the least weight of both machinery and propellant results. Most of the difficulty in turbine and pump matching is caused by each component having its own best speed. For example, the components of a hydrogen-fluorine turbopump are shown in table I. The 116-pound fluorine pump is cavitation limited to 4100 rpm. The 214-pound hydrogen pump is loading limited at 11,000 rpm. The best turbine weighs 70 pounds and operates at 30,000 rpm.

Table II shows the results of the matching study for these pumps and turbines. Four pump and turbine arrangements were considered. If everything is run on one shaft at the fluorine speed, 4100 rpm, the fluorine pump weighs 116 pounds, the hydrogen pump, 2020 pounds, and the impossible turbine, 4000 pounds. By putting a gear with an estimated weight of 294 pounds between the turbine and the two pumps, the over-all weight is reduced from 6136 to 2500 pounds.

A better way would be to run the hydrogen pump and turbine together at the hydrogen pump speed of 11,000 rpm and to gear down to the fluorine pump. In this case the gear is estimated to weigh 120 pounds and the turbine, 600 pounds. The over-all weight is now 1050 pounds, which is quite an improvement. In the final arrangement, each component could be operated at its best speed by using a gear to each pump. For this case, the total weight is 720 pounds. Mechanical considerations such as thrust-bearing requirements for the geared hydrogen pump or the turbine flow rate could govern the choice between these last two considerations.

The results of similar matching studies for four propellant combinations are shown in figure 14. The turbopump weight, consisting of complete pumps, gears, and the turbine, but without the gas generator or piping and valving, is expressed as a ratio to the total propellant weight for a range of pressures in the propellant tanks. For this example, the vapor pressures of hydrogen, oxygen, fluorine, and RP-1 were taken to be 20, 18, 18, and 0.2 pounds per square inch absolute, respectively. Mixture ratios are given by the percentage of fuel in the labels for each curve.

From figure 14 it is evident that the turbopump for RP-1 - oxygen is the lightest. The heaviest turbopump was for the hydrogen-oxygen combination, where 24 percent hydrogen was used. As the percentage of hydrogen is reduced, the turbopump weight ratio is also reduced. For the hydrogen-fluorine combination with 6 percent hydrogen, turbopump weight ratios very similar to the RP-1 - oxygen combination were obtained.

CONCLUDING REMARKS

The results of a simplified analysis of the turbopump component of a liquid-propellant rocket propulsion system indicate that:

1. Hydrogen pumps are considerably heavier per pound of propellant pumped than pumps designed for heavier liquids.

2. Although the use of hydrogen requires much higher turbine power to drive the hydrogen pump, the higher energy per pound available to the turbine allows the turbine flow (percent of pump flow) to remain the same as for more conventional propellants.

3. Turbines for use with the high-energy propellant combinations will require high specific work and multiple stages to extract the available energy.

[redacted]

4. In order to reduce turbopump weight, at least one and possibly both pumps will have to be geared to the turbine.

5. For lean mixture ratios, the over-all turbopump weight of a hydrogen-fluorine combination compares favorably with the more conventional RP-1 - oxygen combination.

6. The weight dependence of pumps at low values of suction head requires an optimization between turbopump and propellant tank weight for an optimum rocket vehicle design.

4793-I

REFERENCE

1. Jacobs, Robert B., Martin, Kenneth B., Van Wylen, Gordon J., and Birmingham, Bascom W.: Pumping Cryogenic Liquids. Tech. Memo. No. 36, Rep. 3569, Cryogenic Eng. Lab., NBS, Feb. 24, 1956.

[redacted]

OPTIMUM COMPONENTS FOR HYDROGEN - FLUORINE TURBOPUMP

COMPONENT	WEIGHT	RPM
FLUORINE PUMP	116 LB	4,100
HYDROGEN PUMP	214 LB	11,000
TURBINE	70 LB	30,000

CS-14817

Table I

MATCHING OF PUMPS AND TURBINE

ARRANGEMENT	FLUORINE PUMP	HYDROGEN PUMP	TURBINE	GEARS	TOTAL
SINGLE SHAFT	116 LB 4100 RPM	2020 LB 4100 RPM	4000 LB 4100 RPM		6136 LB
GEARED TURBINE	116 LB 4100 RPM	2020 LB 4100 RPM	70 LB 30,000 RPM	294 LB	2500 LB
GEARED F_2 PUMP	116 LB 4100 RPM	214 LB 11,000 RPM	600 LB 11,000 RPM	120 LB	1050 LB
GEARED F_2 AND H_2 PUMPS	116 LB 4100 RPM	214 LB 11,000 RPM	70 LB 30,000 RPM	320 LB	720 LB

CS-14815

Table II

CAVITATION ON A HYDROFOIL

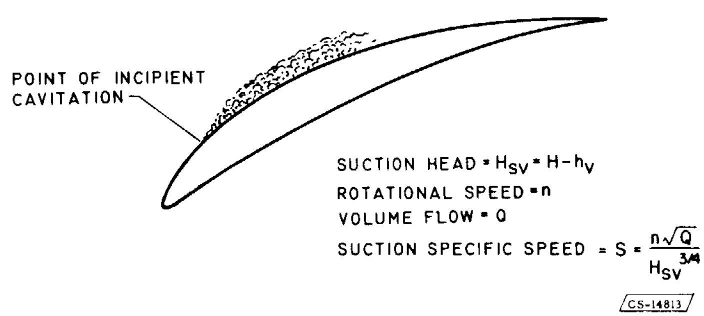

Figure 1

PRESSURE DISTRIBUTION ON A HYDROFOIL FOR AN AXIAL FLOW PUMP

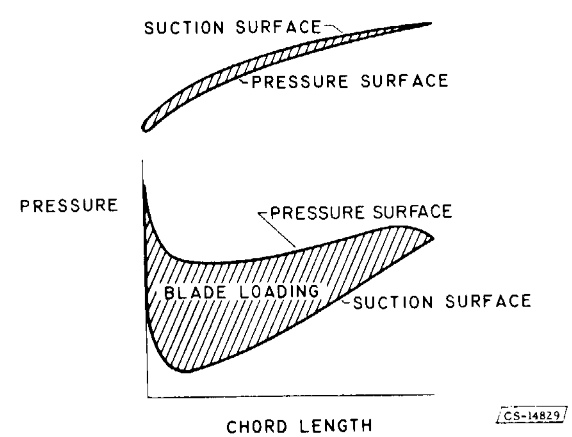

Figure 2

[redacted]

VELOCITY DISTRIBUTION ON A CENTRIFUGAL PUMP BLADE

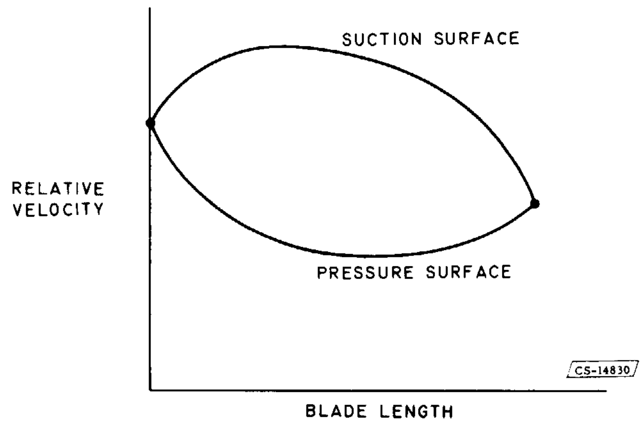

Figure 3

EFFECT OF CAVITATION LIMITS ON WEIGHT OF LARGE HYDROGEN PUMP

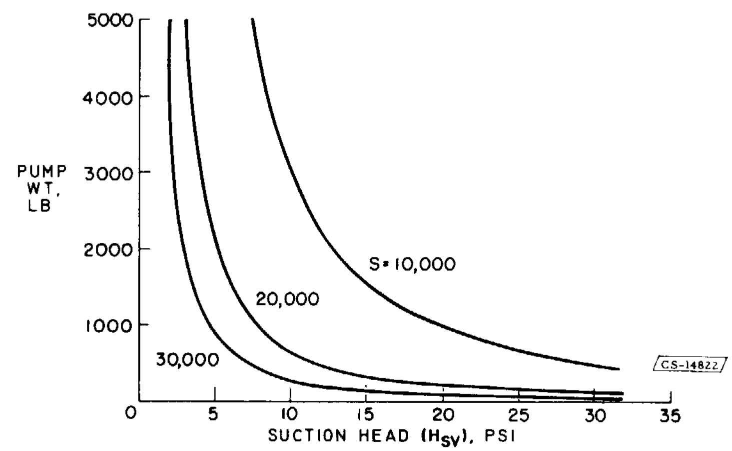

Figure 4

EFFECT OF CAVITATION AND LOADING LIMITS ON WEIGHT OF LARGE HYDROGEN PUMP

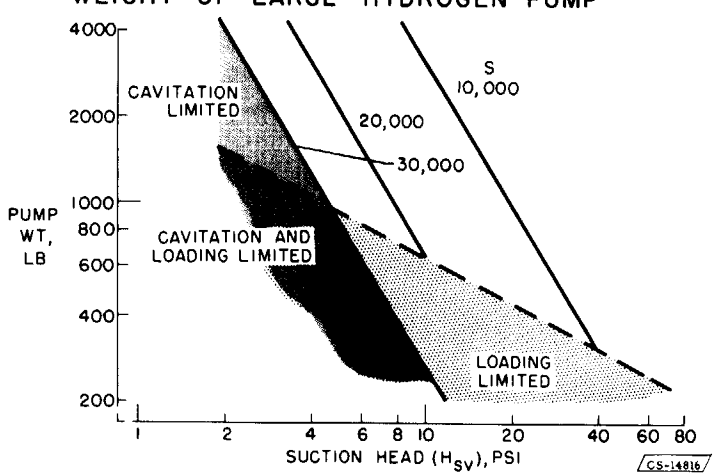

Figure 5

EFFECT OF PROPELLANT ON PUMP WEIGHT

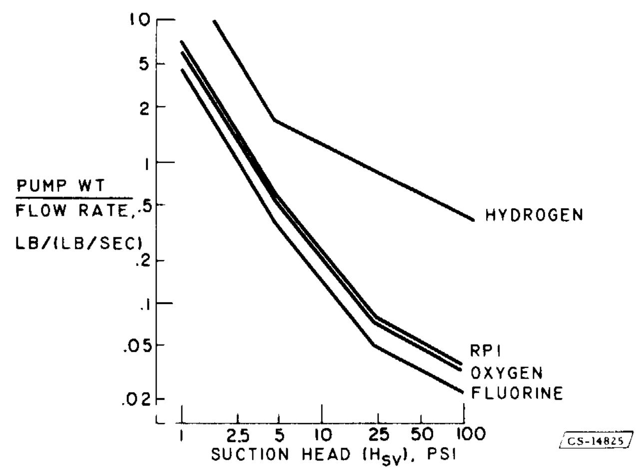

Figure 6

[redacted]

EFFECT OF HYDROGEN - FLUORINE MIXTURE ON PUMP WEIGHT

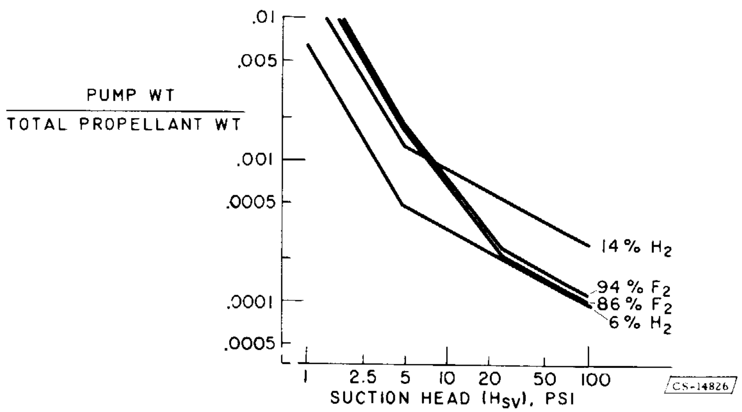

Figure 7

EFFECT OF TURBINE FLOW ON MISSILE GROSS WEIGHT

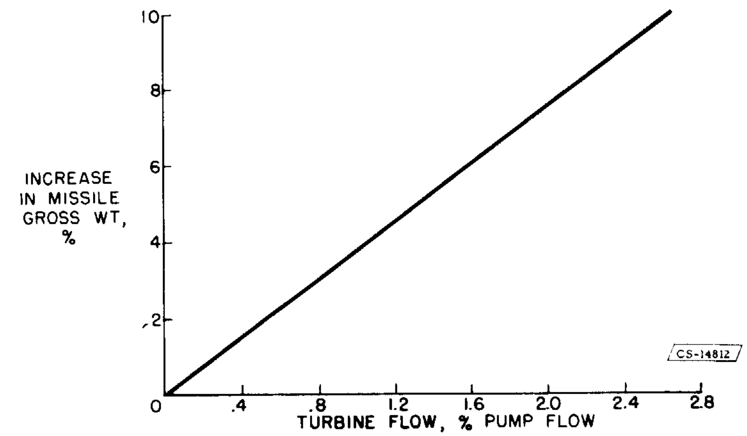

Figure 8

EFFECT OF TURBINE FLOW AND TURBINE WEIGHT ON MISSILE GROSS WEIGHT

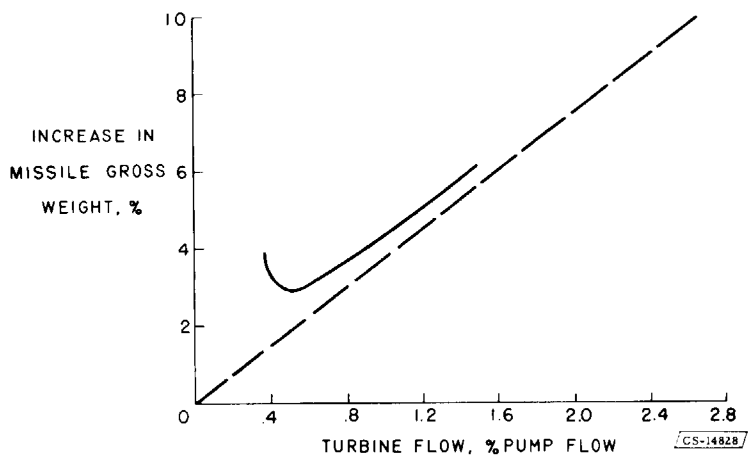

Figure 9

EFFECT OF TURBINE FLOW ON TURBINE WEIGHT

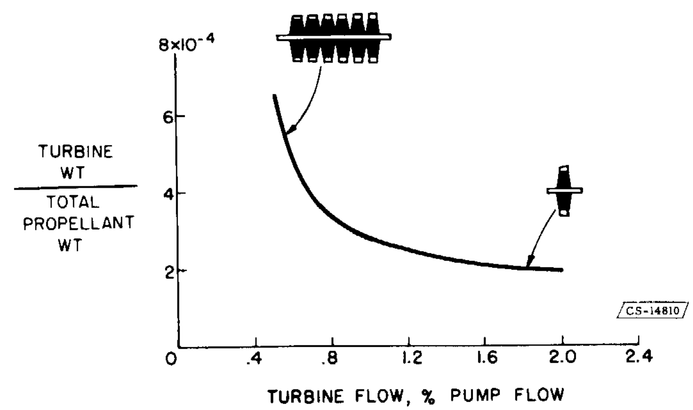

Figure 10

EFFECT OF PROPELLANT COMBINATIONS ON TURBINE FLOW

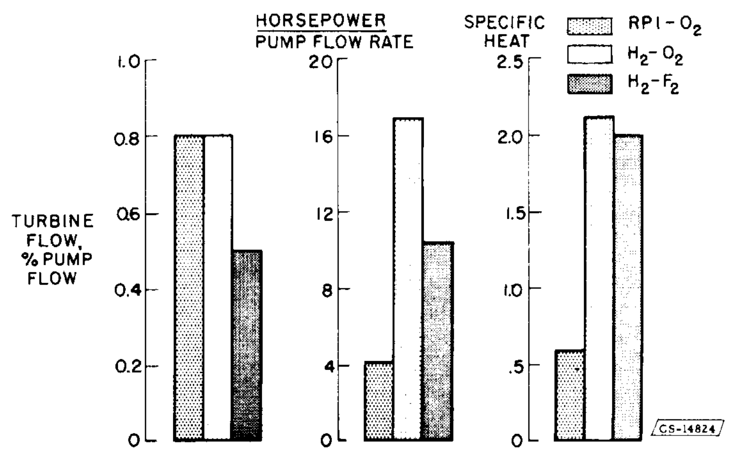

Figure 11

EFFECT OF PROPELLANT COMBINATIONS ON TURBINE DIAMETER AND STAGE NUMBER

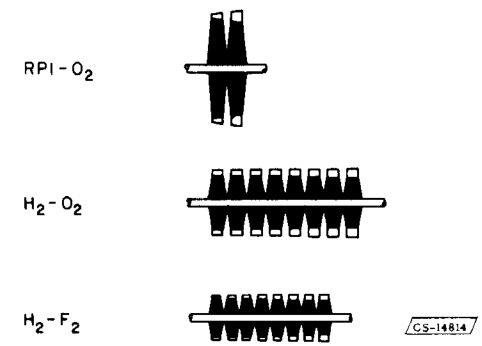

Figure 12

EFFECT OF PROPELLANT COMBINATIONS ON TURBINE WEIGHT

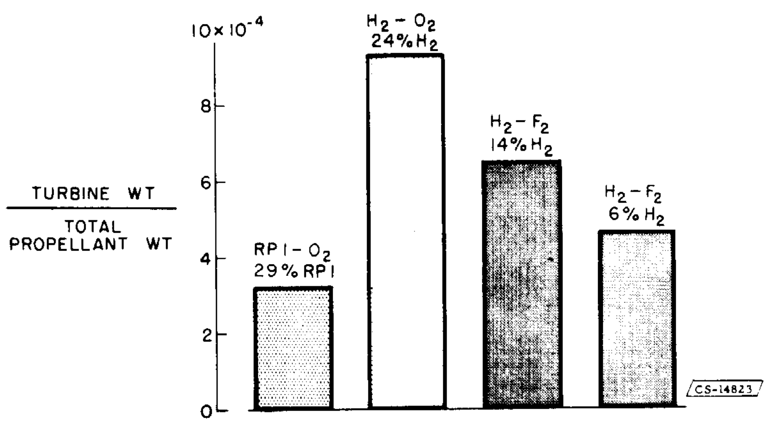

Figure 13

EFFECT OF PROPELLANT ON TURBOPUMP WEIGHT

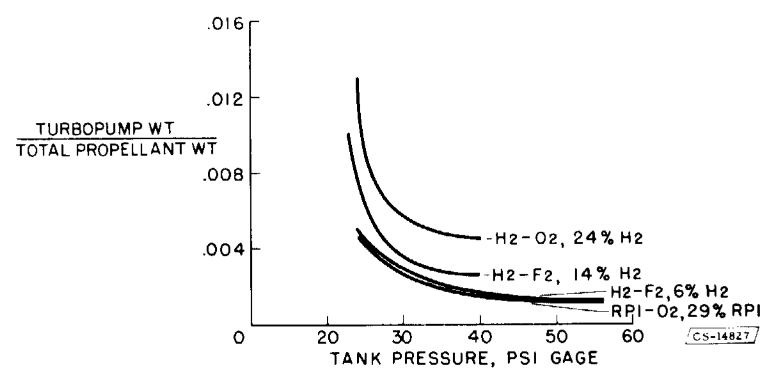

Figure 14